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A novel building energy efficiency evaluation index: Establishment of calculation model and application

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ABSTRACT

In current system of building energy efficiency, the building energy saving rate is calculated based on energy consumption per unit area on a certain past stage. The approach is restricted by the development of economy, progress of energy-saving technologies and climate change. In present work, a novel building energy efficiency evaluation index is developed to represent building energy saving performance. A building model can be first established according to architectural design scheme, current standards and operating conditions. Then, average daily indoor air temperature would be obtained using hourly outdoor air temperature as input conditions, with the one-dimensional unsteady heat transfer model. Finally, the calculation equations of energy saving of envelopes (ΔS) and building energy saving rate (BESR) are derived. In application, a building envelopes trade-off option is proposed and a target building in Western China is employed for case study. The results indicate that, about 19.3% of whole energy achieving indoor human thermal comfort is provided by building envelopes for the target building. The parametric analyses indicate that, BESRs of the standard building model in cold climate zone (2A) are much higher than those in cold climate zone (2B) in China. It is found that, the trade-off option can also be employed to select and optimize insulation materials and layer thicknesses. The approach can provide new thoughts for evaluation of energy saving performance of building envelopes in the design phase.

1. Introduction

With quick progress of economic development of developing countries, world energy consumption indicates a rapid growth trend in recent years. Building energy conservation started from the first world energy crisis in 1973 and has been developed rapidly for past forty years. In China, the building industry achieved high-speed development and the total construction area had been exceeded 56.1 billion m^2 in 2014 [1]. Energy consumption of building sector increased from 0.289 to 0.677 billion tons of standard coal, from 2000 to 2010. According to related predictions with life cycle approach, energy consumption in building sector would account for more than 43% of the overall energy consumption in China in recent years [2].

The factors that affect building energy consumption are mainly climate conditions [3], climate change [4], thermal performance of building envelopes (walls, floors, doors, windows, etc, which can hold indoor space and generate thermal environment) [5,6], indoor human thermal comfort demand [7], operating efficiency of heating, ventilation and air conditioning (HVAC) systems [8], operating mode of buildings [9] and occupant behaviours [10]. Therefore, to reduce energy consumption in building sector, there are mainly two kinds of approaches. The one is in the design phase, to adjust building envelopes to adapt local climate conditions [11]. The other is to improve operating efficiency of HVAC systems, operating mode of buildings and occupant behaviours during operating period [12]. It has been recognized that the former one is the foundation for energy conservation in buildings [13].

To reduce building energy consumption and guide building energy efficiency design, different design strategies of energy saving have been proposed. The major countries in the world have developed corresponding standards and codes. National standards from most European countries limited energy demand for new buildings [14]. There were generally two ways, one was to set minimum insulation requirements for building components. The other was to set maximum energy demand for the whole buildings. ASHRAE Standard 90.1 [15] also established specific indicators for thermal performance of envelopes. Additionally, mandatory requirements of lightning and HVAC systems were proposed. It can be obtained that mandatory requirements of basic parameters of buildings and energy use systems were key ways to reduce building energy consumption. With the development of building

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Nomenclature

a	beginning date of counting building energy efficiency, dimensionless
b	ending date of counting building energy efficiency, dimensionless
c	specific heat, $J{\cdot}kg^{-1}{\cdot}°C^{-1}$
$f_{comf}(x)$	annual average comfortable temperature curve, dimensionless
$f_{in}(x)$	annual indoor air temperature curve, dimensionless
$f_{out}(x)$	annual outdoor air temperature curve, dimensionless
F	area of walls and roofs, m^2
F_c	area of external windows, m^2
$H_{d,h}$	direct solar radiation on the horizontal plane (hourly values), $kJ{\cdot}m^{-2}{\cdot}h^{-1}$
$H_{s,h}$	scattering radiation on the horizontal plane (hourly values), $kJ{\cdot}m^{-2}{\cdot}h^{-1}$
$H_{t,h}$	total solar radiation on the horizontal plane (hourly values), $kJ{\cdot}m^{-2}{\cdot}h^{-1}$
$H_{t,v}$	total solar radiation on the vertical plane (hourly values), $kJ{\cdot}m^{-2}{\cdot}h^{-1}$
I	solar radiation intensity (hourly values), $W{\cdot}m^{-2}$
J	building energy saving rate, %
J_a	energy saving rate of actual building model, %
J_s	energy saving rate of standard building model, %
$J_{w\tau}$	cooling load intensity due to heat gain of windows without shading device, $W{\cdot}m^{-2}$
k	heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}°C^{-1}$
k_c	heat transfer coefficient of external windows, $W{\cdot}m^{-2}{\cdot}°C^{-1}$
l	counting days of building energy efficiency, dimensionless
N	ventilation rate, h^{-1}
N_0	number of days, dimensionless
Q_c	indoor cooling load due to heat gain of windows (hourly values), W
R_d	ratio of direct solar radiation on the vertical and horizontal plane (hourly values), dimensionless
S	baseline of building energy consumption, °C·d
S'	design building energy consumption, °C·d
t	temperature, °C
t_{sa}	outdoor sol–air temperature (hourly values), °C
$\bar{t}_{D,in}$	average indoor air temperature (daily values), °C
$\bar{t}_{D,out}$	average outdoor air temperature (daily values), °C
V	volume of room, m^3
w_s	sunset angle on the horizontal plane, dimensionless
w_s'	sunset angle on the south plane, dimensionless
X_d	site correction factor, dimensionless
X_g	construction correction factor of the window, dimensionless
$y_{D,out}$	deviation between $\bar{t}_{D,out}$ and $f_{comf}(x)$, °C

Greek letters

α_1	convective heat transfer coefficient between indoor air and the first layer of external walls (or roofs), $W{\cdot}m^{-2}{\cdot}°C^{-1}$
α_2	convective heat transfer coefficient between outdoor air and the nth layer of external walls (or the mth layer of roofs), $W{\cdot}m^{-2}{\cdot}°C^{-1}$
γ	declination of sun, °
δ	thickness, m
ΔS	energy saving of building envelopes, °C·d
$\Delta\tau$	time step, s
η_1	transmission efficiency of heat-supply network,%
η_2	boiler operating efficiency,%
λ	thermal conductivity, $W{\cdot}m^{-1}{\cdot}°C^{-1}$
ρ_{gr}	reflection coefficient of the ground against solar radiation, dimensionless
ρ_{in}	density of indoor air, $kg{\cdot}m^{-3}$
ρ_{out}	density of outdoor air, $kg{\cdot}m^{-3}$
ρ_s	absorption coefficient of solar radiation, dimensionless
τ	time, s
φ	local geographic latitude, °

Subscripts

1	1st layer of external walls or roofs
a	actual
D	Dth day
e	east
i	ith hour
in	indoor
m	mth layer of roofs
n	nth layer of external walls, north
out	outdoor
r	roofs
s	standard, south
w	external walls, west
x	xth layer of external walls
y	yth layer of roofs
z	values at $\tau = z{\cdot}\Delta\tau$
z + 1	values at $\tau = (z+1){\cdot}\Delta\tau$

Abbreviations

BESR	building energy saving rate
CHTC	convective heat transfer coefficient
HTC	heat transfer coefficient
HVAC	heating, ventilation and air conditioning
TMY	typical meteorological year

energy conservation, energy efficiency index could be increased continuously, especially for the thermal parameters of building envelopes (see Table 1 [16]). Taking UK for an example, heat transfer coefficient (HTC) of external walls, roofs, floors and windows reduced by 22%, 36%, 44% and 33% from 1995 to 2000.

Energy saving rate in buildings was first proposed in Europe since 1973. For European countries with a large proportion of heating load, energy consumption per unit area at one certain stage is employed as a base, to calculate building energy saving rate. For instance, energy consumption of residential buildings before the energy crisis is treated as a base in France. In the beginning, energy saving rate was set 25%. After that, the energy saving rate was advanced by 25% twice, respectively. Recently, the index was improved by 25% and 40% based on the previous basis (for different types of buildings), respectively. By taking both advanced experience of building energy conservation from Europe and America, also considering development phase of China, the Chinese Government published the first design standard on residential

Table 1
Development process of HTC in Building Regulations in UK [16]

Element	HTC ($W{\cdot}m^{-2}{\cdot}°C^{-1}$)		Percentage reduction (%)
	1995 standard	2000 standard	
Walls	0.45	0.35	22
Roofs	0.25	0.16	36
Floors	0.45	0.25	44
Windows	3.30	2.20	33

building energy efficiency in severe cold and cold zones in 1986. After that, different standards on energy conservation of residential buildings in different climate zones had been enacted and revised by 2010. Related standards on energy conservation of public buildings were also enacted in 2015 [17]. The index of building energy saving rate (BESR) was proposed as a key constraint of energy conservation design of buildings, which was constantly changing during different periods. For instance, BESR in severe cold and cold zones of China is presented in Table 2 [18–20]. Development history of energy conservation in buildings of China is illustrated in Fig. 1. It could be observed that BESR had been increased from 30% to 65% from 1986 to 2010. In particular, BESR mentioned above is calculated based on the field survey data of a group of typical buildings in heating period from 1980 to 1981, which is regarded as a base of building energy consumption. The energy consumption is decreased by 30%, 50% and 65% on the foundation of baseline of building energy consumption [21].

To achieve energy conservation in buildings, the share of building envelopes and energy use systems in total energy saving target are restricted according to standards of the world. For instance, Table 3 [18–20] lists main indexes of building envelopes and heating systems in different standards for residential buildings in Xi'an (Capital of Shaanxi Province, a representative city in cold zone of China). BESR was increased step by step due to the improvement of thermal performance of building envelopes and heating system coefficients. However, fixed proportion of energy saving amount and limited quantitative index lead to the loss of possibility that architects can make full use of design tactics to improve the thermal performance of buildings. Therefore, there are some problems using current BESR to evaluate energy saving performance of buildings, which are listed as follows:

(1) Determination method for baseline of building energy consumption is unscientific and inaccurate. Calculation process of BESR depends largely on the selection of baseline of building energy consumption. However, the present standards select heating energy consumption of buildings in certain climate zone during certain period (a certain stage before world energy crisis in Europe and 1980–1981 in China) as the baseline of building energy consumption, which fails to reference energy consumption performance of buildings in other climate zones and other types of building. What's more, the quick development in building sector in recent years should be taken into account. Therefore, BESR based on current baseline of building energy consumption can't comprehensively indicate the energy saving level.
(2) Energy saving index of building envelopes and HVAC systems are mutually independent. Specifically, these two aspects share responsibility for completing the task of energy saving, but they can't be compensated by one another. Performance improvement of one part doesn't mean that the design objective of the other part can be reduced. Actually, these two parts should be complementary and improving energy saving performance of building envelopes should be treated as the highest priority.
(3) There is lack of unified standards for building energy efficiency in different climate zones [22]. At present, different types of buildings in different climate zones perform different standards and codes, which are different in mandatory provision and energy saving indexes. Therefore, there is no uniform and impartial scale for the judgement of building energy saving performance, with the result that energy saving design of buildings themselves is hard to be compared. What's worse is that the role of building envelopes in energy saving can't be evaluated scientifically.

What about recent studies related to this issue? Actually, related investigations have been conducted to achieve building energy efficiency. To adjust indoor air temperature and reduce energy consumption, phase change materials are integrated with building envelopes. Liu et al. [23] defined the energy saving rate based on heating and cooling load with and without the energy-saving technology. The purpose of the study was to evaluate energy saving potential among different climates conditions and design parameters of phase change wall. Giancola et al. [24] and Sanchez et al. [25] employed Stereo-PIV approach and numerical simulation method to investigate energy saving performance of Open Joint Ventilated Facades. In another study [26], a multi-objective particle swarm optimization was employed to find a set of solutions to improve the building energy saving performance in four climatic regions of Iran. The optimized results can reduce the annual total building electricity consumption as much as 11.3%. The reduction was the deviation of electricity consumption before and after using the optimization method. However, the individual contribution of the building envelopes and HVAC systems can't be obtained by the approach. It can be found that, quantitative calculation of building energy saving performance is significantly essential and still unsolved.

According to above investigations, there are some limitations adopting current BESR as the index of constraints and evaluation of building energy saving performance. Therefore, it is imperative to redefine BESR to accelerate the development of energy conservation in building sector. In present work, a novel approach for representation of building energy saving performance is proposed, which could encourage architects to improve energy saving performance by means of design tactics. A mathematical model is established to describe heat transfer process between building envelopes and indoor and outdoor air. Average daily indoor and outdoor air temperature (determined with human thermal comfort demand and typical meteorological year (TMY) data, respectively) are employed to calculate baseline of building energy consumption. Solar radiation and heat transfer through transparent envelopes are also taken into consideration in the calculation model. Furthermore, a method for building envelopes trade-off option is established with the proposed calculation model of BESR. The influences of climate conditions, different types and thicknesses of insulation layer on the BESR are carefully investigated.

2. Development of the BESR calculation model

In present work, the virtual building energy consumption is introduced to calculate the proposed BESR, which is no longer about actual energy consumption in construction and operating period of buildings. Air temperature is the main indicator for description of indoor and outdoor thermal environment, which also has major impact on cooling and heating load of HVAC systems [27]. What kind of data and parameters can be adopted for the calculation, hourly or daily data of air temperature? Due to current calculation of energy consumption and building load in engineering practice mainly based on daily data, especially for indoor air temperature. Therefore, daily average indoor and outdoor air temperature are selected as critical parameters to evaluate building energy consumption. The proposed BESR is determined as follows:

$$J = \frac{S - S'}{S} \times 100\% \tag{1}$$

Table 2
Comparisons on BESR among different standards of residential buildings in severe cold and cold zones in China.

Year	Standard number	Standard name	BESR (%)
1986	JGJ26-1986	Design standard for energy efficiency of residential buildings [18]	30
1995	JGJ26-95	Design standard for energy efficiency of residential buildings (heating residential building) [19]	50
2010	JGJ26-2010	Design standard for energy efficiency of residential buildings in severe could and cold zones [20]	65

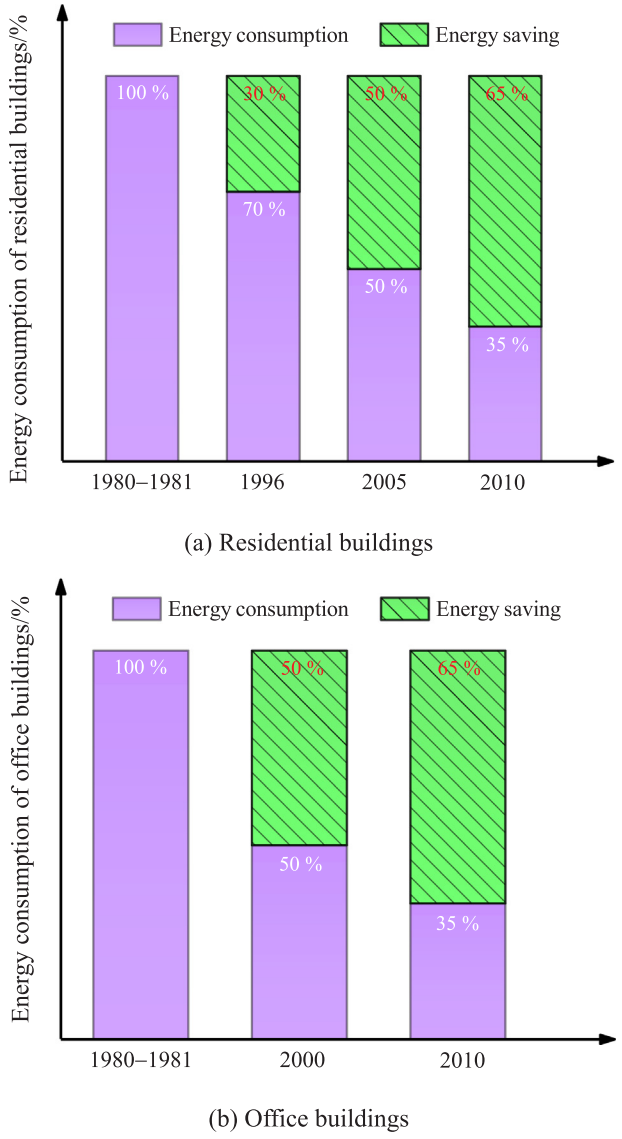


Fig. 1. Development of building energy conservation in China.

Table 3
Comparisons on main indexes of building envelopes and heating systems between different standards for residential buildings in Xi'an.

Standard number	HTC ($W{\cdot}m^{-2}{\cdot}°C^{-1}$)			Heating system efficiency (%)	
	Walls	Windows	Roofs	η_1	η_2
JGJ26-1986 [18]	1.6	6.4	1.0	85	55
JGJ26-95 [19]	1.0	4.7	0.6	90	68
JGJ26-2010 [20]	0.6	2.8	0.45	92	70

where J is the BESR; S' is the design energy consumption in buildings; S is the baseline of energy consumption in buildings, which is defined as the energy consumption to eliminate deviation between indoor human thermal comfort demand and outdoor climate conditions. In past years, indoor human thermal comfort demand has been clearly defined [28]. Furthermore, outdoor climate conditions at certain location are relatively stable without considering climate change. Therefore, the baseline of building energy consumption proposed in present work is unique. S-S' is the energy saving of building envelopes. Relations between and among outdoor climate conditions, building envelopes and indoor human thermal comfort demand are illustrated in Fig. 2. The detailed derivation process of the novel BESR is as follows:

2.1. Average daily outdoor air temperature

Outdoor air temperature curve ($f_{out}(x)$) in Fig. 2 is generated with average daily outdoor air temperature ($\bar{t}_{D,out}$). Values of $\bar{t}_{D,out}$ could be obtained by averaging hourly outdoor air temperature in TMY weather data [29]. TMY weather data contains hourly values for dry-bulb temperature, solar radiation intensity on the horizontal plane and direct solar radiation intensity in normal direction, etc. All the weather files of main cities from all over the world are available in Ref. [30].

2.2. Average daily indoor air temperature

Based on different materials of building envelopes, the walls and roofs are divided into n and m layers from indoor to outdoor, respectively. The center points on each layer are selected as computing nodes of temperatures. To obtain the values of average daily indoor air temperature ($\bar{t}_{D,in}$), we make following assumptions to simplify the physical model.

(1) One-dimensional unsteady state heat transfer occurs in building envelopes. The effect of thermal bridge is neglected.
(2) Thermal resistance of ground is infinite, which means it is adiabatic in present model.
(3) The indoor space is treated as a system of particles with a certain thermal capacity. Therefore, indoor air temperature is uniform at a certain time.

Thermal process in building envelopes is illustrated in Fig. 3. For natural operating buildings, the heat balance equation can be expressed as:

$$c\rho_{in}V\frac{dt_{D,i,in}}{d\tau} = k_{w,in}F_w(t_{w,1}-t_{D,i,in}) + k_{r,in}F_r(t_{r,1}-t_{D,i,in}) + (t_{D,i,out}-t_{D,i,in})(c\rho_{out}VN/3600 + F_c\cdot k_c) + Q_c \quad (2)$$

where c is the specific heat; ρ_{in} and ρ_{out} are the density of indoor and outdoor air, respectively; V is the volume of study room; $t_{D,i,in}$ and $t_{D,i,out}$ are the indoor and outdoor air temperature at Dth day and ith hour; τ is the time; $k_{w,in}$ is the HTC between the indoor air and the first layer of external walls; $k_{r,in}$ is the HTC between the indoor air and the first layer of roofs; F_w and F_r are the areas of external walls and roofs; $t_{w,1}$ and $t_{r,1}$ are the temperature of the first layer of external walls and roofs; N is the ventilation rate; F_c is the area of external windows; k_c is the HTC of external windows; Q_c is the hourly indoor cooling load due to heat gain of windows.

To solve Eq. (2), the heat balance equations of each layer in external

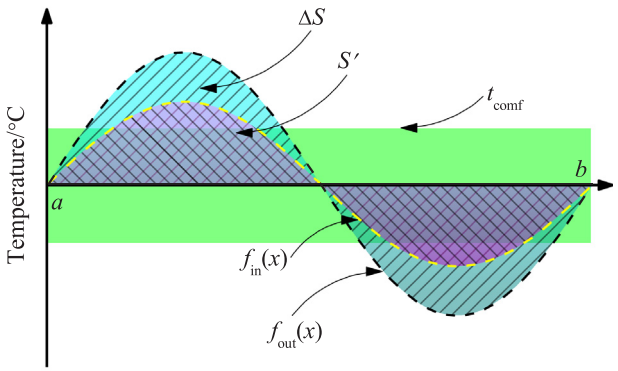


Fig. 2. Relations between and among climate conditions, building envelopes and human thermal comfort demand.

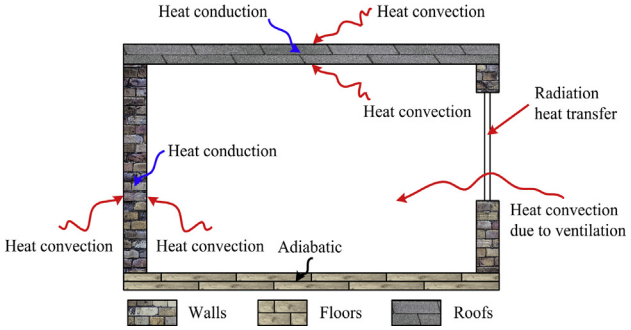


Fig. 3. Thermal process of building envelopes.

walls and roofs could be established. Schematic diagram of different layers and computing nodes in external walls and roofs are shown in Fig. 4. The heat balance equations at xth (x = 1, 2, …, n) layer of external walls are expressed as follows:

$$\begin{cases} x = 1, c_{w,1}F_w\delta_{w,1}\rho_{w,1}\dfrac{dt_{w,1}}{d\tau} = k_{w,in}F_w(t_{D,i,in}-t_{w,1}) + k_{w,1}F_w(t_{w,2}-t_{w,1}) \\ 2 \leqslant x \leqslant n-1, c_{w,x}F_w\delta_{w,x}\rho_{w,x}\dfrac{dt_{w,x}}{d\tau} = k_{w,x-1}F_w(t_{w,x-1}-t_{w,x}) \\ \quad + k_{w,x}F_w(t_{w,x+1}-t_{w,x}) \\ x = n, c_{w,n}F_w\delta_{w,n}\rho_{w,n}\dfrac{dt_{w,n}}{d\tau} = k_{w,n-1}F_w(t_{w,n-1}-t_{w,n}) + k_{w,out}F_w(t_{sa}-t_{w,n}) \end{cases} \tag{3}$$

The heat balance equations at yth (y = 1, 2, …, m) layer of roofs are as follows:

$$\begin{cases} y = 1, c_{r,1}F_r\delta_{r,1}\rho_{r,1}\dfrac{dt_{r,1}}{d\tau} = k_{r,in}F_r(t_{D,i,in}-t_{r,1}) + k_{r,1}F_r(t_{r,2}-t_{r,1}) \\ 2 \leqslant y \leqslant m-1, c_{r,y}F_r\delta_{r,x}\rho_{r,y}\dfrac{dt_{r,y}}{d\tau} = k_{r,y-1}F_r(t_{r,y-1}-t_{r,y}) + k_{r,y}F_r(t_{r,y+1}-t_{r,y}) \\ y = m, c_{r,m}F_r\delta_{r,m}\rho_{r,m}\dfrac{dt_{r,m}}{d\tau} = k_{r,m-1}F_r(t_{r,m-1}-t_{r,m}) + k_{r,out}F_r(t_{sa}-t_{r,m}) \end{cases} \tag{4}$$

where $k_{w,x}$ is the HTC between xth and (x + 1)th layer of external walls; $k_{r,y}$ is the HTC between yth and (y + 1)th layer of roofs; $k_{w,out}$ is the HTC between the outdoor air and the nth layer of external walls; $k_{r,out}$ is the HTC between the outdoor air and the mth layer of roofs; t_{sa} is the hourly outdoor sol–air temperature; $t_{w,x}$ and $t_{r,y}$ are the average temperature of the xth and yth layer of external walls and roofs.

Parameters involved in Eqs. (2)-(4) are calculated as:

$$k_{w,in} = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_{w,1}}{2\lambda_{w,1}}} \tag{5}$$

$$k_{w,x} = \frac{1}{\frac{\delta_{w,x}}{2\lambda_{w,x}} + \frac{\delta_{w,x+1}}{2\lambda_{w,x+1}}} \tag{6}$$

$$k_{w,out} = \frac{1}{\frac{1}{\alpha_2} + \frac{\delta_{w,n}}{2\lambda_{w,n}}} \tag{7}$$

where α_1 is convective heat transfer coefficient (CHTC) between indoor air and the first layer of external walls (or roofs); α_2 is the CHTC between outdoor air and the nth layer of external walls (or the mth layer of roofs); $\delta_{w,1}$, $\delta_{w,x}$ and $\delta_{w,n}$ are the thickness of the 1st, xth and nth layer of external walls; $\lambda_{w,1}$, $\lambda_{w,x}$ and $\lambda_{w,n}$ are the conductivity of the 1st, xth and nth layer of external walls.$k_{r,in}$, $k_{r,y}$ and $k_{r,out}$ could also be obtained with the following equations:

$$k_{r,in} = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_{r,1}}{2\lambda_{r,1}}} \tag{8}$$

$$k_{r,y} = \frac{1}{\frac{\delta_{r,y}}{2\lambda_{r,y}} + \frac{\delta_{r,y+1}}{2\lambda_{r,y+1}}} \tag{9}$$

$$k_{r,out} = \frac{1}{\frac{1}{\alpha_2} + \frac{\delta_{r,m}}{2\lambda_{r,m}}} \tag{10}$$

where $\delta_{r,1}$, $\delta_{r,y}$ and $\delta_{r,m}$ are the thickness of the 1st, yth and mth layer of roofs; $\lambda_{r,1}$, $\lambda_{r,y}$ and $\lambda_{r,m}$ are the conductivity of the 1st, yth and mth layer of roofs.t_{sa} can be calculated as follows:

$$t_{sa} = t_{D,i,out} + \frac{\rho_s I}{\alpha_2} \tag{11}$$

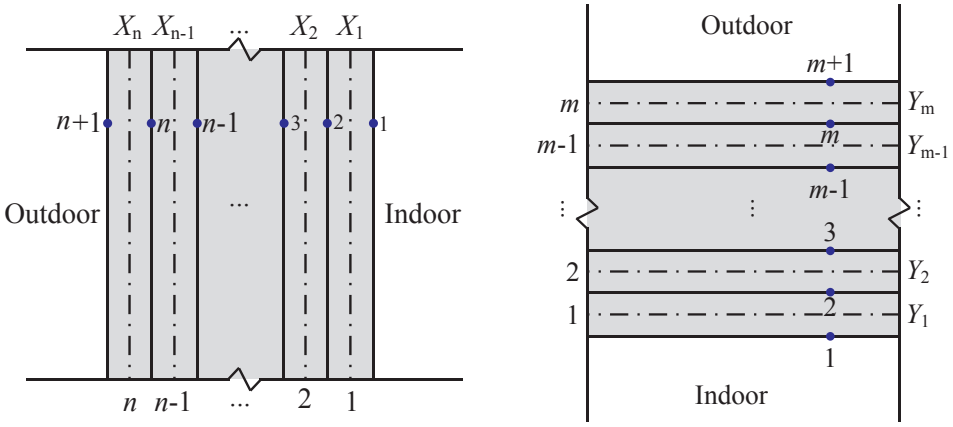
where ρ_s is the absorption coefficient of solar radiation; I is the hourly solar radiation intensity on the horizontal or vertical plane.

Hourly solar radiation in different directions can be calculated as follows [31]:

$$H_{t,v} = H_{d,h}R_d + H_{s,h}\left(\frac{1+\cos\theta}{2}\right) + H_{t,h}\rho_{gr}\left(\frac{1-\cos\theta}{2}\right) \tag{12}$$

where $H_{t,v}$ is the hourly total solar radiation on the vertical plane; $H_{d,h}$ is the hourly direct solar radiation on the horizontal plane; $H_{s,h}$ is the hourly scattering radiation on the horizontal plane; $H_{t,h}$ is the hourly total solar radiation on the horizontal plane; ρ_{gr} is the reflection coefficient of the ground against solar radiation; θ is the angle between the ground and walls; R_d is the ratio of hourly direct solar radiation on the vertical and horizontal plane, which is expressed as follows [31]:

$$R_{d,s} = \frac{\sin\varphi\cdot\cos\gamma\cdot\sin\omega_s' + (\pi/180)\cdot\omega_s'\cdot(-\cos\varphi)\cdot\sin\gamma}{\cos\varphi\cdot\cos\gamma\cdot\sin\omega_s + (\pi/180)\cdot\omega_s\cdot\sin\varphi\cdot\sin\gamma} \tag{13}$$



(a) External walls (b) Roofs

Fig. 4. Schematic diagram of different layers and computing nodes.

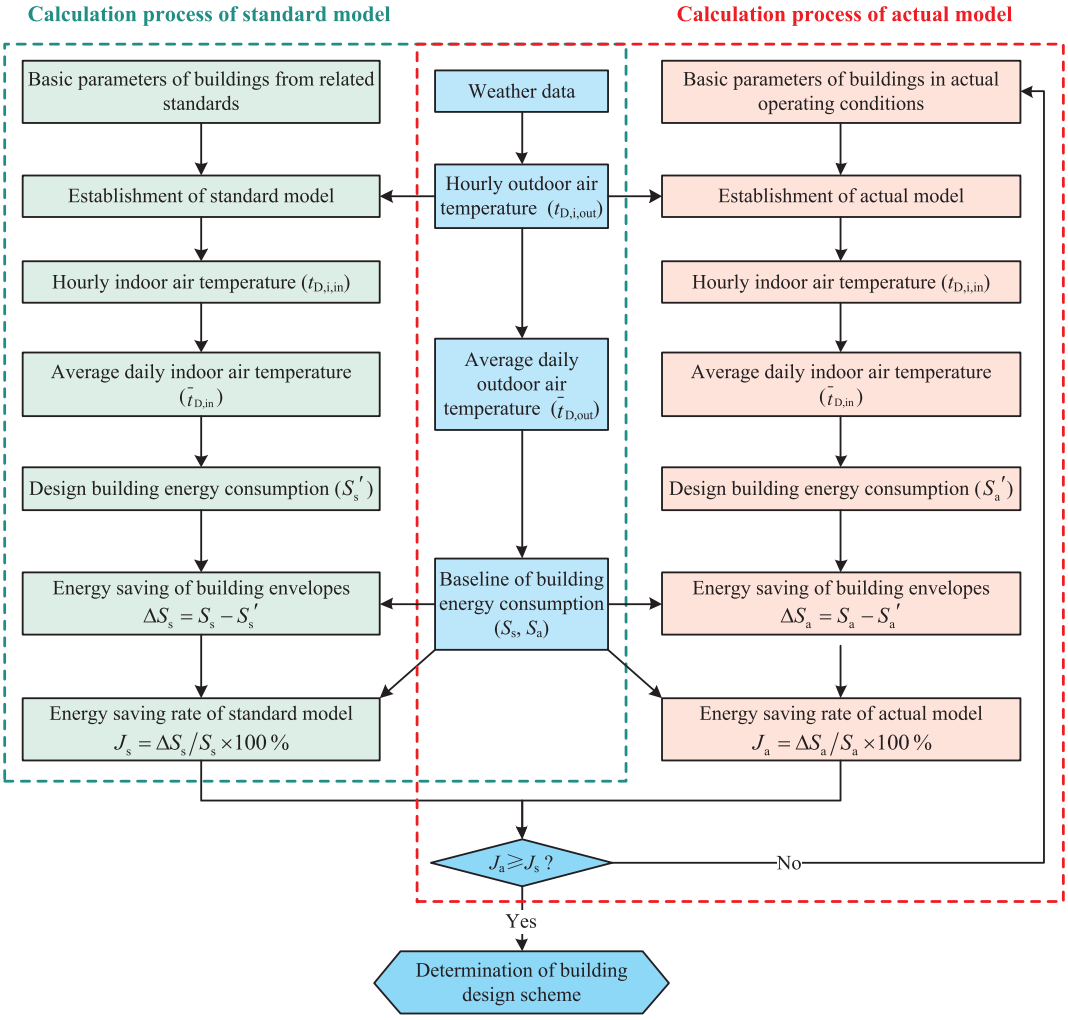

Calculation process of standard model
Calculation process of actual model
Basic parameters of buildings from related standards
Weather data
Basic parameters of buildings in actual operating conditions
Establishment of standard model
Hourly outdoor air temperature ($t_{D,i,out}$)
Establishment of actual model
Hourly indoor air temperature ($t_{D,i,in}$)
Hourly indoor air temperature ($t_{D,i,in}$)
Average daily indoor air temperature ($\bar{t}_{D,in}$)
Average daily outdoor air temperature ($\bar{t}_{D,out}$)
Average daily indoor air temperature ($\bar{t}_{D,in}$)
Design building energy consumption (S_s')
Design building energy consumption (S_a')
Energy saving of building envelopes $\Delta S_s = S_s - S_s'$
Baseline of building energy consumption (S_s, S_a)
Energy saving of building envelopes $\Delta S_a = S_a - S_a'$
Energy saving rate of standard model $J_s = \Delta S_s / S_s \times 100\,\%$
Energy saving rate of actual model $J_a = \Delta S_a / S_a \times 100\,\%$
$J_a \geqslant J_s$?
No
Yes
Determination of building design scheme

Fig. 5. Flow chart of building energy conservation design with building envelopes trade-off option.

Table 4
Parameters of building envelopes of standard model.

Dimensions	Height (m)	Length (m)	Width (m)	Shape coefficient	Window-wall ratio
	4.55	20	10	0.52	South: 0.5, North: 0.3
k (W·m^{-2}·°C^{-1})	Roofs	External walls	South windows		North windows
	0.35	0.45	1.8		2.5

Table 5
Parameters of external walls for calculating BESR in standard model.

Layer index	$\delta_{w,x}$ (m)	$c_{w,x}$ (J·kg^{-1}·°C^{-1})	$\rho_{w,x}$ (kg·m^{-3})	$\lambda_{w,x}$ (W·m^{-1}·°C^{-1})
1st	0.02	1050	1800	0.93
2nd	0.24	1050	1800	0.81
3rd	0.02	1050	1800	0.93
4th	0.07	1386	20	0.041
5th	0.02	1050	1800	0.93

$$R_{d,e} = R_{d,w} = \frac{\cos\gamma\cdot(1-\cos\omega_s)}{2(\cos\varphi\cdot\cos\gamma\cdot\sin\omega_s + (\pi/180)\cdot\omega_s\cdot\sin\varphi\cdot\sin\gamma)} \quad (14)$$

$$R_{d,n} = \frac{\sin\gamma\cdot\cos\varphi\cdot\sin|\omega_s-\omega_s'|-\cos\gamma\cdot\sin\varphi\cdot|\sin\omega_s-\sin\omega_s'|}{\cos\varphi\cdot\cos\gamma\cdot\sin\omega_s + (\pi/180)\cdot\omega_s\cdot\sin\varphi\cdot\sin\gamma} \quad (15)$$

Table 6
Parameters of roofs for calculating BESR of standard model.

Layer index	$\delta_{r,x}$ (m)	$c_{r,x}$ (J·kg^{-1}·°C^{-1})	$\rho_{r,x}$ (kg·m^{-3})	$\lambda_{r,x}$ (W·m^{-1}·°C^{-1})
1st	0.02	1050	1700	0.87
2nd	0.10	920	2500	1.74
3rd	0.06	920	1000	0.29
4th	0.07	1386	30	0.042
5th	0.15	800	700	0.22
6th	0.03	920	2100	1.28
7th	0.01	1471	600	0.17

Table 7
Parameters of windows for calculating BESR of standard model.

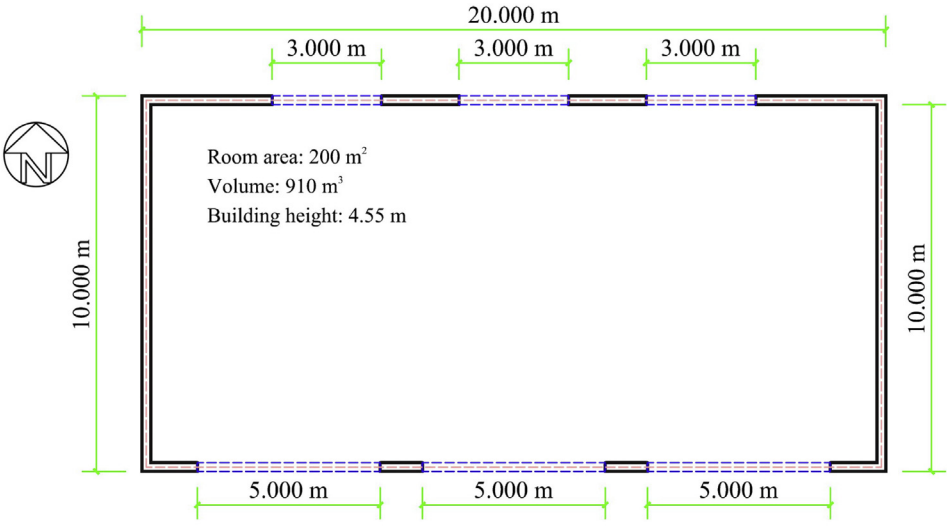
Orientation	F_c (m^2)	k_c (W·m^{-2}·°C^{-1})	X_g	X_d
South	45.5	1.8	0.44	1.0
North	27.3	2.5	0.35	1.0

where φ is the local geographic latitude; γ is the declination of sun; w_s and w_s' are the sunset angle on the horizontal and south plane, which could be calculated as follows [31]:

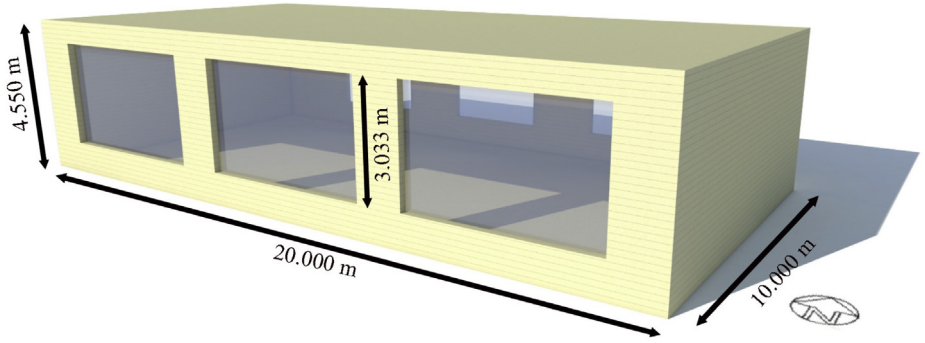
$$\omega_s = \cos^{-1}(-\tan\varphi\cdot\tan\gamma) \quad (16)$$

$$\omega_s' = \min(\cos^{-1}(-\tan\varphi\cdot\tan\gamma),\cos^{-1}(-\tan(\varphi-\theta)\cdot\tan\gamma)) \quad (17)$$

Declination of sun (γ) can be calculated with the following equation



(a) Floor plan



(b) Detailed sizes

Fig. 6. Floor plan and detailed sizes of standard building model.

[31]:

$$A = \frac{2\pi(N_0-1)}{365} \tag{18}$$

$$\gamma = 0.006918-0.399912\cos A + 0.070257\sin A-0.006758\cos 2A + 0.000907\sin 2A-0.002697\cos 3A + 0.00148\sin 3A \tag{19}$$

where N_0 is number of days, beginning from January 1st.

Q_c in Eq. (2) can be calculated by [32]:

$$Q_c = F_c \cdot X_g \cdot X_d \cdot J_{w\tau} \tag{20}$$

where X_g is the construction correction factor of windows; X_d is the site correction factor; $J_{w\tau}$ is the cooling load intensity due to heat gain of windows without shading device.

During the solutions, Eqs. (2)-(4) can be converted to difference equations by replacing $d\tau$, $dt_{D,i,in}$, $dt_{w,x}$ and $dt_{r,y}$ by Δt, $t^{z+1}_{D,i,in}-t^{z}_{D,i,in}$, $t^{z+1}_{w,x}-t^{z}_{w,x}$ and $t^{z+1}_{r,y}-t^{z}_{r,y}$, respectively [33]. Superscript z and $z+1$ represent values at $\tau = z\cdot\Delta\tau$ and $\tau = (z+1)\cdot\Delta\tau$. $\Delta\tau$ is set 3600 s. The transformed equations are expressed as follows:

$$t^{z+1}_{D,i,in} = \frac{\begin{array}{c} c\rho_{in}Vt^{z}_{D,i,in}/3600 + k_{w,in}F_w t^{z}_{w,1} + k_{r,in}F_r t^{z}_{r,1} \\ + t^{z}_{D,i,out}(c\rho_{out}VN/3600 + F_c\cdot k_c) + Q^{z}_{c} \end{array}}{c\rho_{in}V/3600 + k_{w,in}F_w + k_{r,in}F_r + c\rho_{out}VN/3600 + F_c\cdot k_c} \tag{21}$$

For external walls:

$$\begin{cases} x = 1, t^{z+1}_{w,1} = \dfrac{c_{w,1}F_w\delta_{w,1}\rho_{w,1}t^{z}_{w,1}/3600 + k_{w,in}F_w t^{z}_{D,i,in} + k_{w,1}F_w t^{z}_{w,2}}{c_{w,1}F_w\delta_{w,1}\rho_{w,1}/3600 + k_{w,in}F_w + k_{w,1}F_w} \\ 2 \leqslant x \leqslant n-1, t^{z+1}_{w,x} = \dfrac{c_{w,x}F_w\delta_{w,x}\rho_{w,x}t^{z}_{w,x}/3600 + k_{w,x-1}F_w t^{z}_{w,x-1} + k_{w,x}F_w t^{z}_{w,x+1}}{c_{w,x}F_w\delta_{w,x}\rho_{w,x}/3600 + k_{w,x-1}F_w + k_{w,x}F_w} \\ x = n, t^{z+1}_{w,n} = \dfrac{c_{w,n}F_w\delta_{w,n}\rho_{w,n}t^{z}_{w,n}/3600 + k_{w,n-1}F_w t^{z}_{w,n-1} + k_{w,out}F_w t^{z}_{sa}}{c_{w,n}F_w\delta_{w,n}\rho_{w,n}/3600 + k_{w,n-1}F_w + k_{w,out}F_w} \end{cases} \tag{22}$$

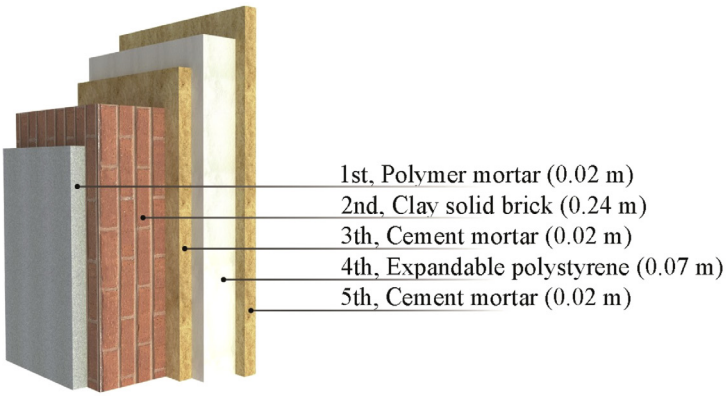
For roofs:

$$\begin{cases} y = 1, t^{z+1}_{r,1} = \dfrac{c_{r,1}F_r\delta_{r,1}\rho_{r,1}t^{z}_{r,1}/3600 + k_{r,in}F_r t^{z}_{D,i,in} + k_{r,1}F_r t^{z}_{r,2}}{c_{r,1}F_r\delta_{r,1}\rho_{r,1}/3600 + k_{r,in}F_r + k_{r,1}F_r} \\ 2 \leqslant y \leqslant m-1, t^{z+1}_{r,y} = \dfrac{c_{r,y}F_r\delta_{r,y}\rho_{r,y}t^{z}_{r,y}/3600 + k_{r,y-1}F_r t^{z}_{r,y-1} + k_{r,y}F_r t^{z}_{r,y+1}}{c_{r,y}F_r\delta_{r,y}\rho_{r,y}/3600 + k_{r,y-1}F_r + k_{r,y}F_r} \\ y = m, t^{z+1}_{r,m} = \dfrac{c_{r,m}F_r\delta_{r,m}\rho_{r,m}t^{z}_{r,m}/3600 + k_{r,m-1}F_r t^{z}_{r,m-1} + k_{r,out}F_r t^{z}_{sa}}{c_{r,m}F_r\delta_{r,m}\rho_{r,m}/3600 + k_{r,m-1}F_r + k_{r,out}F_r} \end{cases} \tag{23}$$

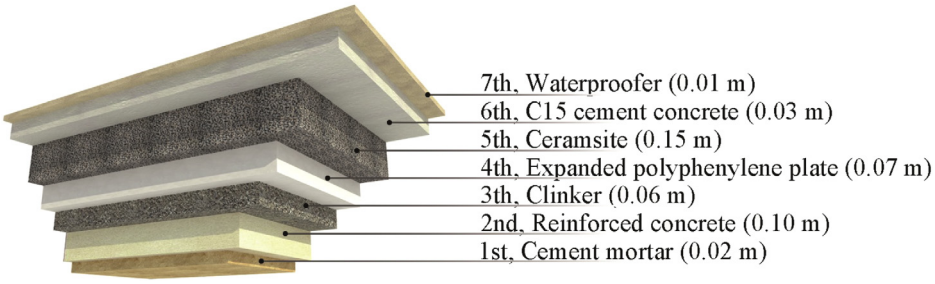
Hourly indoor air temperature ($t_{D,i,in}$) can be obtained based on Eqs. (21)-(23). Therefore, average daily indoor air temperature ($\bar{t}_{D,in}$) could be obtained by averaging $t_{D,i,in}$ in a certain day.

2.3. Baseline of building energy consumption

Annual outdoor air temperature curve ($f_{out}(x)$) could be generated with average daily outdoor air temperature ($\bar{t}_{D,out}$). Baseline of building energy consumption (S) is represented by the enclosed area between $f_{out}(x)$ and annual average comfortable temperature curve ($f_{comf}(x)$):


1st, Polymer mortar (0.02 m)
2nd, Clay solid brick (0.24 m)
3th, Cement mortar (0.02 m)
4th, Expandable polystyrene (0.07 m)
5th, Cement mortar (0.02 m)

(a) External walls


7th, Waterproofer (0.01 m)
6th, C15 cement concrete (0.03 m)
5th, Ceramsite (0.15 m)
4th, Expanded polyphenylene plate (0.07 m)
3th, Clinker (0.06 m)
2nd, Reinforced concrete (0.10 m)
1st, Cement mortar (0.02 m)

(b) Roofs

Fig. 7. Structural details of external walls and roofs.

Table 8
Hourly values of cooling load intensity due to heat gain of windows without shading device in Xi'an [32]

Time		0	1	2	3	4	5	6	7	8	9	10	11
$J_{wτ}$ (W·m^{-2})	South	29	25	21	18	16	13	21	35	50	69	95	124
	North	27	22	19	16	14	10	31	51	59	72	85	96
Time		12	13	14	15	16	17	18	19	20	21	22	23
$J_{wτ}$ (W·m^{-2})	South	148	161	161	149	132	116	98	75	60	50	41	35
	North	106	112	115	114	108	103	102	75	57	47	38	32

$$S = \int_a^b f_{out}(x)dx = \sum_{D=1}^{l} y_{D,out}\Delta x = \frac{b-a}{l}\sum_{D=1}^{l} y_D \tag{24}$$

where a and b represent beginning and ending date of counting building energy efficiency (0 and 365, respectively); l is the counting days of building energy efficiency (3 6 5); $y_{D,out}$ is the deviation between average daily outdoor air temperature ($\bar{t}_{D,out}$) and annual average comfortable temperature curve ($f_{comf}(x)$). Baseline of building energy consumption could be obtained with the following equation:

$$S = \frac{b-a}{l}\sum_{D=1}^{l} y_{D,out} = \sum_{D=1}^{365} |\bar{t}_{D,out} - t_{comf}| \tag{25}$$

2.4. Design building energy consumption

Annual indoor air temperature curve ($f_{in}(x)$) could be generated with average daily outdoor air temperature ($\bar{t}_{D,in}$). Design building energy consumption (S') is represented by the enclosed area between $f_{in}(x)$ and annual average comfortable temperature curve ($f_{comf}(x)$):

$$S = \int_a^b f_{in}(x)dx = \frac{b-a}{l}\sum_{D=1}^{l} y_{D,in}\Delta x = \sum_{D=1}^{365} |\bar{t}_{D,in} - t_{comf}| \tag{26}$$

where $y_{D,in}$ is the deviation between average daily indoor air temperature ($\bar{t}_{D,in}$) and annual average comfortable temperature curve ($f_{comf}(x)$). $\bar{t}_{D,in}$ is the average daily indoor air temperature at Dth day.

2.5. Energy saving of building envelopes

Energy saving of building envelopes (ΔS) represents baseline of building energy consumption that is reduced by building envelopes. Energy saving of building envelopes (ΔS) is represented by the enclosed area between $f_{out}(x)$ and $f_{in}(x)$:

$$\Delta S = S - S' = \sum_{D=1}^{365} |\bar{t}_{D,out} - t_{comf}| - \sum_{D=1}^{365} |\bar{t}_{D,in} - t_{comf}| \tag{27}$$

2.6. Building energy saving rate (BESR)

Finally, the proposed building energy saving rate (BESR, J) is calculated as follows:

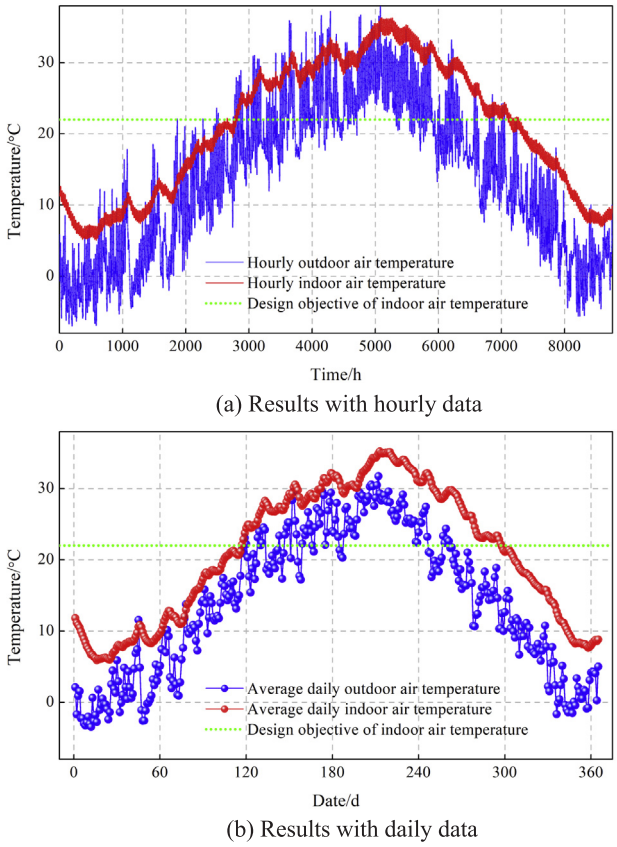


Fig. 8. Calculation results of standard building model with proposed approach.

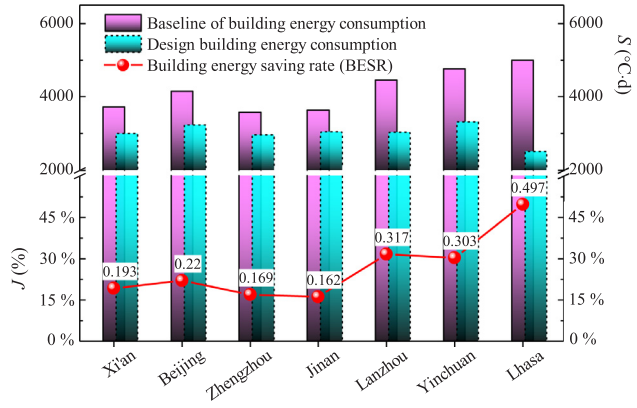


Fig. 9. Building energy saving performance at different climate conditions.

$$J = \frac{\Delta S}{S} \times 100\% = \frac{\sum_{D=1}^{365} |\bar{t}_{D,out} - t_{comf}| - \sum_{D=1}^{365} |\bar{t}_{D,in} - t_{comf}|}{\sum_{D=1}^{365} |\bar{t}_{D,out} - t_{comf}|} \times 100\% \quad (28)$$

All above methods and equations are coded and solved by MATLAB, which are included in Appendix A.

3. Building envelopes trade-off option with BESR

The flowchart of application mode with the proposed BESR, which is a building envelopes trade-off option, is shown in Fig. 5. The method mainly contains two calculation processes: calculation process of standard model and actual model, which are carefully introduced as follows:

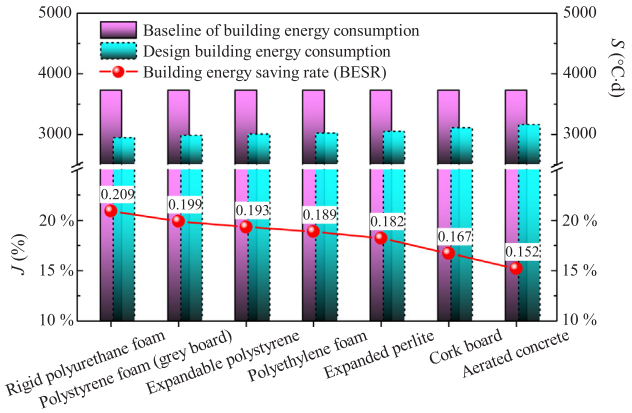


Fig. 10. Building energy saving performance with different insulation materials.

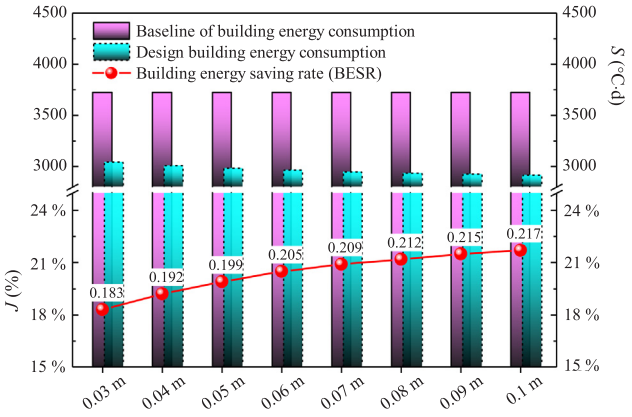


Fig. 11. Building energy saving performance with different thicknesses of insulation layer.

3.1. Calculation process of standard building model

In the first step, BESR of standard building model (J_s) could be calculated. Basic parameters of building envelopes take values based on limited values of related standards on building energy efficiency in countries and regions locally. Specifically, in calculation process of J_s, the values of related parameters are according to design drawings and related standards. In other words, calculation of J_s is based on virtual buildings.

To introduce the trade-off option clearly, a single-story residential building in Western China (Xi'an City) is adopted as the standard building model. To deal with the problems in other climate zones and other types of buildings, specific sizes of buildings and different weather data can be adopted to replace related values in the present model. Xi'an is the capital of Shaanxi Province of China. It is in the cold climate zone but quite close to the boundary of the hot summer and cold winter climate zone. It has distinct seasonal variations with hot summer and cold winter characteristics [34]. The building energy efficiency design is based on the current Design standard for energy efficiency of residential buildings in severe cold and cold zone (JGJ26-2010) [20]. Related parameters of building envelopes take limited values of the standard. We adopt a simplified model, which contains external envelopes without interior envelopes and other structures. Basic parameters of external walls, roofs and windows are listed in Tables 4–7. The floor plan and detailed sizes are illustrated in Fig. 6. Structural details of external walls and roofs are shown in Fig. 7. In Fig. 7(a), the building materials of external walls are polymer mortar (0.02 m), clay solid brick (0.24 m), cement mortar (0.02 m), expandable polystyrene (0.07 m) and cement mortar (0.02 m), from indoor to outdoor. In

Fig. 7(b), the building materials of roofs are cement mortar (0.02 m), reinforced concrete (0.10 m), clinker (0.06 m), expanded polyphenylene plate (0.07 m), ceramsite (0.15 m), C15 cement concrete (0.03 m) and waterproof layer (0.01 m), from indoor to outdoor. CHTC between indoor air and the 1st layer of external walls (or roofs) is 8.7 W/(m^{2}·°C). CHTC between outdoor air and the 4th layer of external walls (or the 7th layer of roofs) is 23.0 W/(m^{2}·°C) [35]. Design objective of indoor air temperature is 22 °C. Ventilation rate is 0.5 per hour. Absorption coefficient of solar radiation of external walls and roofs are 0.65 and 0.70, respectively. Hourly values of cooling load intensity due to heat gain of windows ($J_{w\tau}$) are listed in Table 8 [35].In order to obtain energy saving performance of building envelopes, we assume there is no heat generated and the building is in natural operating mode. Firstly, with the proposed calculating model of BESR, we obtain hourly indoor air temperature with data of hourly outdoor air temperature. And then average daily indoor air temperature is obtained. The annual outdoor air temperature curve ($f_{out}(x)$) and annual indoor air temperature curve ($f_{in}(x)$) are generated with the values of average daily outdoor air temperature ($\bar{t}_{D,out}$) and average daily indoor air temperature ($\bar{t}_{D,in}$), which are illustrated in Fig. 8. For comparisons, the curves generated with hourly data are also expressed. The enclosed areas between $f_{out}(x)$ and $f_{in}(x)$ curves and annual average comfortable temperature curve ($f_{comf}(x)$), which are defined as the baseline of building energy consumption (S_s) and design building energy consumption (S_s'), are calculated. Values of S_s and S_s' of the standard building model are 3726.0 °C·d and 3006.8 °C·d, respectively. Finally, values of energy saving of building envelopes (ΔS_s) and building energy saving rate (J_s) of the standard building model are 719.2 °C·d and 19.3%, respectively. The results indicate that 19.3% of the whole energy consumption can be reduced by building envelopes to achieve indoor thermal comfort. It also means that heating and cooling systems could be adopted to achieve indoor thermal comfort at all time, which could consume about 80.7% of the whole building energy consumption. The above results indicate that, the index of BESR can be employed to obtain the role of building envelopes in energy conservation. The approach can separate corresponding proportion achieved with envelopes from the whole energy saving performance. For the calculation process, the input conditions are local climate conditions, basic sizes of buildings and limited values of envelopes in related standards, etc. In the next section, the calculation model will be adopted to conduct building envelopes trade-off option.

3.2. Calculation process of actual building model

The calculation process of BESR of actual building model (J_a) is similar to J_s, except for values of basic parameters. Unlike J_s, the value of J_a is obtained based on actual design drawings and construction. After obtaining the values of J_a and J_s, they are taken into comparisons to judge the energy saving performance of the actual building. If $J_a \geq J_s$, the conclusion is that the design parameters of the actual building model meet the requirements of current standards on building energy efficiency. If $J_a < J_s$, one or many design parameters in building envelopes could be adjusted without changing design scheme greatly. Then repeat the calculation process of J_a till $J_a > J_s$, which also means the building thermal design accord with related standards. Under the circumstances, the buildings can achieve the goal of energy conservation as well as remain the original design styles of architects.

In parametric analysis, we first compare building energy saving performance at different climate conditions, which is illustrated in Fig. 9. The layer thickness of insulation layers of external walls is 0.07 m. Since all the selected cities are in cold climate zone in China and they have the same construction details and basic parameters. It can be observed that BESRs of the standard building model in cold climate zone (2A) are higher than those in cold climate zone (2B). For instance, values of BESR in Lhasa, Yinchuan and Lanzhou are 49.7%, 30.3% and 31.7%, respectively. It means that, building envelopes play more important role in cold climate zone (2A). The results reinforce that, the climates conditions have significant influences on building energy consumption of building envelopes. The values of BESR in Fig. 9 can be treated as the J_s, which can be employed to conduct the building envelopes trade-off option. The values of J_s in Fig. 9 are also the minimum values for the actual building model which meet relevant standards. Generally, related limited values in building energy conservation standards are just on the climate zone level. Therefore, it is difficult to compare energy saving performance of buildings among different cities in the same climate zone, with the former method. For comparisons among different climate zones, the situation becomes more complicated. However, with the approach proposed in present work, the barrier is broken down. The comparisons among different cities in the same climate zone and even different climate zones can be conducted. The building energy saving performance is no longer necessary to be compared with related values in a certain stage (for example, 1981 in China). The BESR of actual building model just needs to be compared with that of standard building model, whose values are obtained according to current standards.

We also investigate the influences of thermophysical parameters of insulation layers on energy saving performance of building envelopes (see Fig. 10). The building model is the same as expressed in Fig. 6 and the climate conditions in Xi'an are selected for calculation. We compare seven main thermal insulation materials in external walls, keeping the roof unchanged. The thermal conductivities of selected materials are 0.024 W·m^{-1}·°C^{-1}, 0.033 W·m^{-1}·°C^{-1}, 0.041 W·m^{-1}·°C^{-1}, 0.047 W·m^{-1}·°C^{-1}, 0.058 W·m^{-1}·°C^{-1}, 0.093 W·m^{-1}·°C^{-1} and 0.24 W·m^{-1}·°C^{-1}, respectively. The curve of BESR indicates a significant downward trend, with the decrease of thermal conductivity. For the building envelopes trade-off option, all the situations that the thermal conductivities are larger than 0.041 W·m^{-1}·°C^{-1} (with 0.07 m insulation layer), can't satisfy the current standards. Therefore, the proposed trade-off option can be easily adopted to select thermal insulation materials. The impacts of different thermal insulation layer thicknesses are also examined, which are demonstrated in Fig. 11. Rigid polyurethane form is adopted for thermal insulation layer. Other calculation conditions are in accord with those adopted in Figs. 9 and 10. It can be obtained from Fig. 11 that, the energy saving performance of envelopes increase with thermal insulation layer thicknesses. It can also be found that, the growth is slowing down with the increase of insulation layer thicknesses. The building envelopes trade-off option can be satisfied when the layer thickness is larger than 0.05 m. The results also indicate that the thickness of thermal insulation layer could be reduced 0.02 m when replacing expandable polystyrene in standard building model with rigid polyurethane form. It can be also obtained from Fig. 11 that, the BESR doesn't increase linearly with the thickness of insulation layer. That is to say, increasing the thickness of insulation layer endlessly is not the optimal solution for building energy conservation. Both the costs and benefits of the increasing should be taken into consideration. Since building materials and layer thickness are determined based on engineering design atlas and experience, it may lead to unreasonable and imprecise results. To obtain more accurate results, more time and computing resource would be consumed. What's more, it is inconvenient for architects to launch energy consumption simulation to assist in the completion of design. While the proposed approach provides a quantitative calculation method to select and optimize building materials and layer thicknesses, without complicated calculation process using dynamic computing softwares (such as EnergyPlus).

3.3. Application conditions of the trade-off option

What needs to be pointed out is that structure and space of actual buildings are more complicated than the building model shown in Fig. 6. The methodology showed herein focuses on a single-story residential building. Hence, the results cannot be directly extrapolated

and generalized to more complex models. When conducting building envelopes trade-off option of complicated buildings, the parameters can be adjusted according to different types of buildings and different design standards of energy efficiency. For the purpose of sharing, the calculation procedure is in the Appendix A. Program source code by MATLAB, could also be adjusted partially. The proposed calculation model of BESR is a new attempt to determine building energy saving performance, which takes the most important factors (indoor and outdoor air temperature) into consideration. The approach is appropriate for calculating BESR in different climate zones and different types of buildings. With the approach, energy saving performance of building envelopes can be judged simply and accurately with unified baseline. What's more, the approach can help architects compare different design schemes of building envelopes, revise and optimize the original design schemes. In the process, talent of architects is presented to achieve their full potential. More and more distinctive buildings with excellent energy saving performance are built, which will also inherit regional architecture culture.

4. Conclusions

In present work, aiming to solve limitations adopting current BESR as the index of constraints and evaluation of building energy saving performance (1. Unscientific and inaccurate determining method for baseline of building energy consumption, 2. Mutually independent energy saving index of building envelopes and HVAC systems, 3. Lack of unified standards for building energy efficiency in different climate zones), the BESR is redefined to accelerate the development of energy conservation in building sector. Considering the essence of building energy consumption, average daily indoor and outdoor air temperature are employed to calculate baseline of building energy consumption. Adopting the calculation model, an application mode for thermal design of building envelopes is proposed. Based on the approach, energy saving performance of building envelopes can be objectively compared based on the mechanisms of energy consumption. The major contributions are as follows:

(1) An approach that can accurately calculate energy saving performance of building envelopes is established based on revealing interaction mechanism among climate conditions, building envelopes and human thermal comfort. In the approach, related conceptions, methods of taking values and calculation methods are presented. The proposed BESR is calculated with baseline of energy consumption and design energy consumption in buildings, which could be obtained with values of outdoor and indoor average daily air temperature.
(2) For building envelopes thermal design, the trade-off option method is proposed based on the calculation model of BESR. The BESR can be calculated for both standard building model (19.3% in case study) and actual building model. Energy saving rate of actual model (J_a) can be compared with standard model (J_s) to conduct building envelopes trade-off option. The parametric studies indicate that, BESRs of the standard building model for different climate conditions have large deviations, even though the locations are in the same climate zones. Selection and optimization of different insulation materials and layer thicknesses can also be conducted by the trade-off option.

The proposed calculation model would be helpful for comprehensive evaluation of building energy conservation level. Since the current systems from all over the world are similar, the building envelopes trade-off option for thermal design would provide reference for revision of standards on energy conservation in building sector and formulation of building energy conservation policy from all over the world.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enconman.2018.03.090.

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